Spectroscopy in the extreme ultraviolet on an electron beam ion trap

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A compact grazing-incidence spectrometer was implemented on the Livermore electron beam ion trap facility for spectral measurements in the extreme ultraviolet spectral region. The spectrometer employed a 1200 ℓ/mm grating designed for flat-field focusing and a charge coupled device camera for readout. The instrument was used to measure line emission in the range from 25 to 220 Å with a resolving power as high as 600. The performance and calibration of the instrument is described and spectra from highly charged nitrogen and iron ions are presented. Measurements of the *K*-shell spectrum of He-like N^{5+} are presented that confirm earlier wavelength determinations and illustrate the accuracy achievable with the instrument. Our measurement suggests a change in the line identifications of the forbidden He-like N^{5+} transition $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ and of the Li-like N^{4+} collisional satellite transition $1s2s2p\ ^2P_{3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$ observed on the Alcator C-Mod tokamak.
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I. INTRODUCTION

Electron beam ion traps have been shown to be capable of producing virtually any charge state of any element for spectroscopic studies under precisely controlled conditions. The energy of the electron beam can be chosen to select a given ionization state as well as a particular excitation process of interest.[1] The electron density is about $\leqslant 10^{13}$ cm^{-3} so that the measured spectra are directly applicable for comparison with those measured in tokamaks or the Sun. Spectroscopic investigations of the line emission from electron beam ion trap (EBIT) devices have focused predominantly on the x-ray emission[2–4] and, more recently, on optical transitions.[5–7] No investigations have yet been made in the extreme ultraviolet (EUV) regime that connects the range between the soft x-ray and vacuum ultraviolet region.

Line emission from highly charged ions in the EUV regime is very strong and includes the *L*-shell emission from highly charged neon, argon, and iron ions, as well as *M*-shell emission from highly charged iron, krypton, xenon, and tungsten ions. This abundance of line emission in the extreme ultraviolet regime provides important opportunities for the diagnostics of a wide variety of high-temperature plasmas, such as tokamak, laser-produced, and astrophysical plasmas. However, the diagnostic utility of the EUV lines depends on the accuracy of the underlying atomic data. These data are in many instances not very well known; in fact, many lines in this region have not yet been identified. This is true, for example, for many tungsten lines that play an important role in the power balance of tokamaks.[8] Surprisingly, it is also true for lines from iron,[9] despite the fact that iron has much less complex ion states than tungsten. The study of extreme ultraviolet transitions under controlled laboratory conditions is, therefore, crucial for further development of the diagnostic utility of EUV spectra, i.e., for testing the associated atomic data, calibrating atomic physics models, and line identification.

To bridge the gap between the soft x-ray and the vacuum ultraviolet regime at the Livermore EBIT, we have implemented a compact grazing-incidence spectrometer. The new instrument allows us to perform accurate wavelength measurements and to study electron–ion interaction processes in a way similar to previous measurements in the x-ray region. In the following, we describe the instrument and present typical spectra from highly charged nitrogen and iron ions. We discuss wavelength calibration procedures and identify the forbidden $1s^2\ ^1S_0 - 1s2s\ ^3S_1$ transition in helium-like N^{5+}. We distinguish it from the innershell-excited satellite $1s2s2p\ ^2P_{3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$ in Li-like N^{4+} and suggest a change in the identification of this line on the Alcator C-Mod tokamak.[10]

II. SPECTROMETER DESIGN

A schematic diagram of the grazing-incidence spectrometer employed at our EBIT facility is shown in Fig. 1. The spectrometer employed a 1200 ℓ/mm grating mounted on a rotary table. The curved grating was designed for flat-field focusing in the 50–400 Å range, as described by Refs. 11 and 12, and thus has a variable line spacing. Two slitted appertures are used as light and x-ray baffles. They also re-

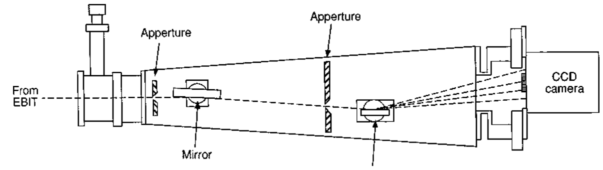

FIG. 1. Layout of the EBIT grazing-incidence spectrometer.

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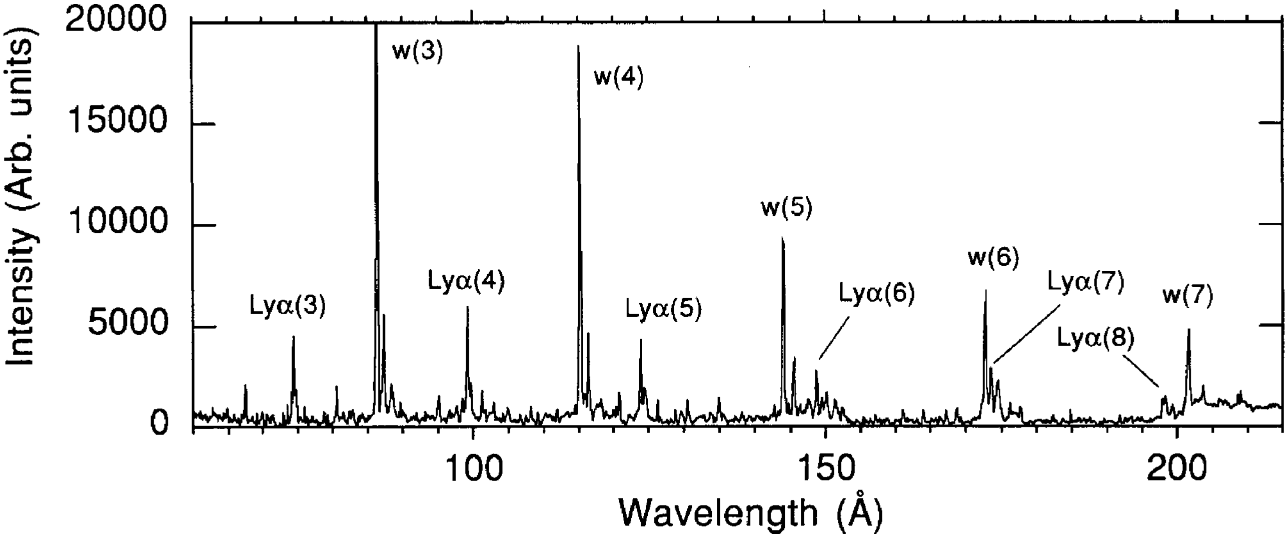

FIG. 2. Spectrum of nitrogen observed in the 60–215 Å region showing the *K*-shell line emission of He-like N^{5+} and H-like N^{6+} in higher orders. The EBIT operation conditions were an electron beam current of 122 mA and an energy of 3.0 keV. The order in which a particular line is observed is given in parentheses.

duce the gas load on EBIT. The latter operates at a pressure of about 10^{-10} Torr, while the former achieves a pressure of only 10^{-7} Torr.

A liquid nitrogen cooled charge coupled device (CCD) camera is used for readout. The camera has 1024×1024 pixels whereby the dimension of each pixel is $25 \times 25\ \mu m^2$. Setting the grating to a 3° incident angle, the distance between the grating and the camera is 23.7 cm. The spectrometer incorporates a rotatable mirror that aids off-line alignment of the grating.

For alignment of the spectrometer on EBIT we make use of the geometric properties of the electron beam in EBIT. The electron beam is about 60 μm in diameter and, therefore, acts as a slit. This property has been used extensively in x-ray measurements.[13,14] In the present case, we make use of this property, and we choose the plane of dispersion of the spectrometer perpendicular to the beam. The mirror is then aligned relative to the electron beam position and the angle between mirror and grating is adjusted to the required value.

The camera is mounted on a moveable holder to allow positioning to different wavelength ranges. The range of movement is 1 in. This effectively doubles the wavelength range that can be accessed with the CCD camera.

III. WAVELENGTH MEASUREMENTS

The calibration of measurements of x-ray wavelengths of highly charged ions on EBIT have relied on recording H-like or He-like reference lines *in situ* (see, e.g., Ref. 15). The wavelength of these lines is well known both theoretically and experimentally. A similar procedure can be used in conjunction with our new EUV spectrometer.

By injecting molecular nitrogen into EBIT and setting the electron beam energy to values well above the threshold to produce N^{6+} ions, we can use the EUV spectrometer to observe the $1s-2p$ Ly$-\alpha$ transitions, as illustrated in Fig. 2. The wavelengths of the two Ly$-\alpha$ fine structure components are 24.7792 and 24.7846 Å.[16] The components are not resolved in our measurement. Assuming statistical populations of the upper levels, we set the wavelength of the unresolved Ly$-\alpha$ transition to 24.7810 ± 0.0004 Å, where the error reflects possible deviations from the assumed upper-level populations.

In the spectrum shown in Fig. 2, which covers the wavelength range 60–215 Å, the Ly$-\alpha$ transitions are observed in third, fourth, fifth, sixth, seventh, and eighth order. Also seen are the *K*-shell transitions from He-like N^{5+} in third, fourth, fifth, sixth, and seventh order.

A closeup of the fourth order spectrum of N^{5+} is shown in Fig. 3. The spectrum shows the resonance line $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, labeled *w*, the intercombination line $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$, labeled *y*, and the forbidden line $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$, labeled *z*. The latter transition is sensitive to the electron density above about 10^{10} cm^{-3}.[17,18] At our densities, estimated to be 2×10^{12} cm^{-3}, its intensity is significantly reduced. Also seen is the $1s2s2p\ ^2P_{3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$ transition in Li-like N^{4+}, labeled *q*, which blends with the weaker transition $1s2s2p\ ^2P_{1/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$ transition in Li-like N^{4+}. A linewidth of

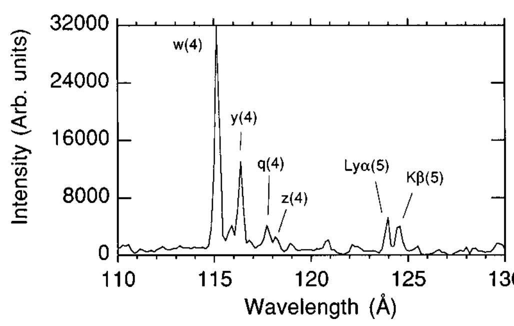

FIG. 3. Detailed view of the fourth-order *K*-shell emission from He-like N^{5+} showing the transitions $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, labeled *w*, the intercombination line $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$, labeled *y*, and the forbidden line $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$, labeled *z*, and the Li-like N^{4+} innershell satellite $1s2s2p\ ^2P_{3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$, labeled *q*.

TABLE I. Summary of the measured wavelengths of N^{5+} and N^{4+}.

Ion	Key	Transition	λ_{theo}	λ_{expt}
N^{5+}	w	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	28.7870[a]	28.7861 ± 0.0022
N^{5+}	y	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	29.0843[a]	29.0835 ± 0.0026
N^{5+}	z	$1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$	29.5347[a]	29.5321 ± 0.0026
N^{4+}	q	$1s2s2p\ ^2P_{3/2} \rightarrow 1s^2 2s\ ^2S_{1/2}$	29.443,[b] 29.5042[c]	29.4135 ± 0.0037

[a]Reference 19.
[b]Reference 21.
[c]Reference 23.

about 0.3 Å can be noted from the spectral data shown. This translates to a resolving power of better than 300 at 100 Å and to better than 600 at 200 Å.

The Ly$-\alpha$ lines in seventh order is blended with other lines, and we use only the positions of the N^{6+} lines in third, fourth, fifth, sixth, and eighth order for wavelength calibration. With this calibration we determined the wavelengths of the He-like resonance line w. A total of 50 values were obtained for the wavelengths of line w observed in different orders in 11 different spectra. The weighted average is 28.7861 Å. The standard error is 0.0019 Å. Including systematic errors, we obtain a value of 28.7861 ± 0.0022 Å for the He-like resonance line. This value agrees very well with the theoretical value of 28.7870 Å calculated by Drake.[19] It also agrees well with a previous high-accuracy measurement, which yielded 28.7872 ± 0.0007 Å.[20] The result for the He-like resonance line w clearly demonstrates the accuracy of our approach within the stated uncertainties.

The same calibration and analysis procedure was used to determine the wavelength of the remaining He-like and Li-like lines in the different orders. The results are summarized in Table I. The He-like results are compared to the theoretical values by Drake[19] and very good agreement is found. The value for line q agrees well with the value of 29.443 Å calculated by Vainshtein and Safronova[21] and the value given by Gabriel and Jordan.[22] It is in disagreement, however, with the newer calculations by Chen, which give 29.504 Å.[23]

The measurement of the eleven nitrogen spectra was spread out over several days. Analyzing the position of a given spectral line as a function of time during the measurement period allowed us to ascertain the spatial stability of the spectrometer. No shifts were found at the statistical level of accuracy.

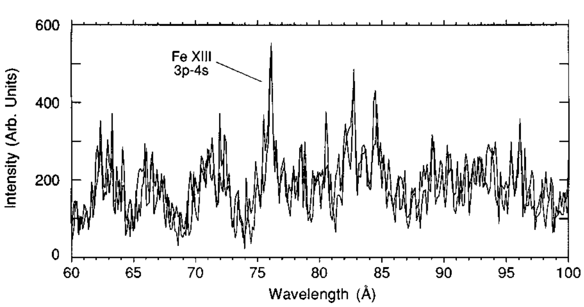

FIG. 4. Line emission spectrum of iron in the extreme ultraviolet measured at the Livermore spectroscopy facility. The electron beam energy was 400 V. Only charge states as high as Fe XIV were produced and excited. Two separate spectra are shown to illustrate reproducibility. The location of the Fe XIII $3p^2 - 3p4s$ transition has been marked.

IV. COMPARISON WITH ALCATOR C-MOD OBSERVATIONS

A recent article by Rice *et al.*[10] studied transport in the edge region of the Alcator tokamak using the He-like N^{5+} and Li-like N^{4+} spectrum. In this article, radial profiles of the lines w, y, and q were computed in the plasma edge region and compared to spectral observations. Line q in the Alcator spectrum was measured to be at 29.52 Å. This wavelength, however, clearly matches that of the He-like line z, which we measured to be at 29.532 ± 0.003 Å. The position of line q by comparison is at 29.414 ± 0.004 (see Table I). The position of line w in the Alcator spectrum, by contrast, was correctly determined to be at 28.78 Å, and the position of line y was determined to be at 29.08 Å, which also matches the value we measured (see Table I). The wavelength calibration of their spectrometer, including the calibration of the wavelength dispersion, thus seems to be correct. We must therefore conclude that the line identified as q in the Alcator spectra is in fact line z.

Because of the high density in the Alcator plasma, which is thought to be more than one order of magnitude higher than the density in in our device, no emission from z is expected. The presence of line z might thus indicate that the density is lower than assumed. Moreover, the charge balance is better than assumed, since no Li-like line is observed at the location of q. Reassigning the feature at 29.52 Å to z from q thus completely changes the inferred transport and charge balance parameters for the Alcator edge region. New studies are clearly warranted to clarify these important issues.

V. IRON *M*-SHELL SPECTROSCOPY

To illustrate the utility of our instrumentation in the extreme ultraviolet regime, we have used the new EBIT grazing-incidence spectrometer to record spectra of the *M*-shell transitions in the low and medium charge states of iron. A spectrum is shown in Fig. 4. Here the electron beam energy was set to 400 eV. As a result, no charge states higher than Fe^{13+} were produced in our trap. The short-wavelength spectrum from such low ionization states is not yet well known, and we have not yet identified most of the lines in this spectrum. This work is in progress and will be reported elsewhere. The measurements show, however, that EUV measurements can be performed on an EBIT.

ACKNOWLEDGMENTS

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